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Human Body Regional Convective Heat Transfer Determination Using Sublimating Naphthalene Disks

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Abstract

The regional convective heat transfer coefficients (h_c) on the human body were determined using sublimating naphthalene disks. Circular naphthalene disks were affixed to various body segments of a stationary, life-size manikin, under constant temperature and wind speed in an environmental chamber. The amount of naphthalene weight loss through sublimation was translated to h_c using the Chilton-Colburn j-factor analogy between heat and mass transfer. The regional convective heat transfer coefficients can be determined by using strictly the heat-mass transfer analogy, excluding any supplementary technique of cylindrical body segment approximations or other shape extrapolations. The logarithmic mean density factor for naphthalene sublimating in air ($P_{AM,n}$) was also determined. $P_{AM,n}$ for the naphthalene-air sublimation environment is only one third of the water vapor-air diffusion environment (P_{AM}). $P_{AM,n}$ is an essential factor for extracting the correct h_c value from the naphthalene mass transfer data.

Nomenclature

c_p = specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)

D_v = mass diffusivity (m^2/s)

h_c = convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)

h_m = naphthalene mass transfer coefficient (m/s)

j_h = Chilton-Colburn analogy j-factor for heat transfer

j_m = Chilton-Colburn analogy j-factor for mass transfer

\dot{m} = naphthalene sublimation weight loss rate ($kg \cdot m^{-2} \cdot s^{-1}$)

P_a = naphthalene vapor pressure in air (assumed = 0)

P_{AM} = logarithmic mean density factor for water vapor diffusion in air (ND)

$P_{AM,n}$ = logarithmic mean density factor for naphthalene sublimating in air (ND)

Pr = Prandtl's number (ND)

P_s = naphthalene surface vapor pressure (Torr or mmHg)

R = naphthalene gas constant ($0.487 \text{ mmHg} \cdot m^3 \cdot kg^{-1} \cdot K^{-1}$)

Sc = Schmidt's number (ND)

T_a = ambient temperature ($^{\circ}K$)

u = air velocity (m)

κ = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)

μ = viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)

ρ = density (kg/m^3)



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Introduction

The Chilton-Colburn j-factor analogy between heat and mass transfer is a well established theory [ASHRAE Fundamentals, 1985]. Since convective heat transfer is not a directly measurable quantity, degree and extent of mass transfer of a sublimating substance (e.g. naphthalene, para-dichlorobenzene) enables the accurate and direct determination of the convective heat transfer coefficient h_c [Sogin, 1958; Kreith et al, 1959; Neal, 1975; Sparrow and Tien, 1977]. The convective heat transfer can then be computed from h_c , incorporating in the surface-to-ambient-air temperature difference. Extensive work in applying the heat-mass transfer analogy in measuring h_c for the human body was reported by Nishi and Gagge [1970a, 1970b]. They attached naphthalene spheres to different body segments on human subjects. The convective transfer of the sphere was then related to the corresponding body segment by approximating the body segment as a cylinder and using known convective relationship between ball and cylinder. In the present study, we used naphthalene disks, and applied only the heat-mass transfer analogy without any body segment shape supplementation. Since the naphthalene disks sat directly on body segments, the regional h_c was measured directly. Extrapolation between different shapes was unnecessary. In applying the heat-mass analogy, Nishi and Gagge bypassed the Chilton-Colburn j-factors by substituting Hilpert's numerical data for cylinders directly into the heat-mass analogy equation. We followed directly and strictly the Chilton-Colburn j-factor equations in developing the present theoretical basis.

Theory of Heat - Mass Transfer Analogy

Mass transfer of naphthalene sublimation h_m can be expressed as [Nishi and Gagge 1970a]

$$h_m = R \cdot T_a \cdot \dot{m} / (P_s - P_a) \quad \{1\}$$

Assuming the heat of sublimation is negligible, P_s may be considered as equal to the saturated vapor pressure at T_a [Sherwood and Träss 1960],

$$\log_{10} P_s = 11.55 - 3765/T_a$$

or,

$$P_s = 10^{(11.55 - 3765/T_a)} \quad \{2\}$$

The Chilton-Colburn analogy j-factor [ASHRAE Fundamentals 1985]

$$\text{for heat transfer} \quad j_h = \frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3}, \quad \text{with } Pr = \frac{c_p \cdot \mu}{\kappa} \quad \{3\}$$

$$\text{for mass transfer} \quad j_m = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3}, \quad \text{with } Sc = \frac{\mu}{\rho \cdot D_v} \quad \{4\}$$

Now, equating the heat and mass transfer j-factors,

$$\frac{h_c}{\rho \cdot c_p \cdot u} (Pr)^{2/3} = \frac{P_{AM,n} \cdot h_m}{u} (Sc)^{2/3}$$

$$h_c = \rho \cdot c_p \left(\frac{Sc}{Pr} \right)^{2/3} \cdot P_{AM,n} \cdot h_m \quad (5)$$

As an example, consider the physical properties of naphthalene vapor transfer at 30°C (typical values):

$$\begin{aligned} \kappa &= 0.02636 \quad \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1} & D_v &= 6.330 \cdot 10^{-6} \quad \text{m}^2/\text{s} \\ c_p &= 1006 \quad \text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} & \rho &= 1.165 \quad \text{kg}/\text{m}^3 \\ \mu &= 1.869 \cdot 10^{-5} \quad \text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \\ Pr &= \frac{c_p \cdot \mu}{\kappa} = 0.7133 & Sc &= \frac{\mu}{\rho \cdot D_v} = 2.535 \\ P_{AM,n} &= 0.319 \quad (\text{for } 0.18 \text{ m/s} < u < 1.8 \text{ m/s}) \end{aligned}$$

Equation (5) then becomes $h_c = 870.6 \cdot h_m$ (6)

Experiment

Circular naphthalene disks were attached to the surface of various body segments on a stationary, life-size (body surface area 1.68 m^2) copper manikin in an environmental chamber. Figure 1 gives a schematic diagram of the manikin and shows the positions of the naphthalene disks on the upper arm, lower arm, thigh, calf and chest. A manikin, rather than human subjects, was used as the appropriate model to avoid the problem of perspiration and thereby eliminate any evaporative contribution usually involved with human subjects.

The environmental chamber was set at an ambient temperature (T_a) of 30°C , with dew point temperature at 5°C . The regional temperature and air velocity were measured at five sites: upper arm, lower arm, thigh, calf, and chest. Figure 1 gives a schematic representation of the locations of naphthalene disks. Omnidirectional thermal anemometers (range 0 - 3 m/s) and thermistor temperature probes were placed approximately 2 cm above and 2 cm away from the naphthalene disk, in such a way as not to disturb the impinging airflow to the disk. Airflow in the chamber was directed normally at the disks. The duration of each experiment was 55 minutes.

Scintillation grade naphthalene with a melting point of approximately 80°C was melted and then poured into aluminum disk casting cassettes. The casting quickly hardens at room temperature, after which a nonadhering cover plate was removed to reveal a smooth naphthalene surface. Immediately after casting, the disks were stored individually in airtight containers. All naphthalene disks were allowed to equilibrate in the chamber at 30°C for 24 hours before using. For the

study, the disks were first mounted into vinyl retainers, which were in turn fastened to the manikin using Velcro straps. Disks were weighed immediately before and after an experiment on a precision balance sensitive to ± 0.01 mg.

To determine the logarithmic mean density factor of naphthalene sublimating in air, $P_{AM,n}$ in equations (4) and (5), a mass transfer experiment similar to that performed by Nishi and Gagge [1970a] was employed. A 1.21 m long magnesium bar was rotated at its center by a stepping electric motor at 10 constant speeds ranging from 3 to 30 rpm, in a still-air chamber. One flat naphthalene disk was attached to each end of the magnesium bar, in such a way that as the bar rotates the naphthalene disks faced normally into the air. The rotation resulted in translational speeds from 0.183 to 1.83 m/s for the disks. Since the chamber had still-air, the translational speeds were also exactly the air velocities that the naphthalene disks were facing. Duration of each experiment was again 55 minutes. From the weight loss data of the rotating naphthalene disks, h_c was computed using equation (5), but without the $P_{AM,n}$ factor, yielding in effect $h_c/P_{AM,n}$. When this rotating disk $h_c/P_{AM,n}$ was compared to true h_c data of comparable wind speed (from Nishi and Gagge [1970a]), a value for $P_{AM,n}$ was then obtained.

RESULTS

Table 1 shows the regional air velocities and local temperatures surrounding the stationary manikin. This level of regional wind speed was maintained throughout the experiment. The local temperatures shown were temperature data averaged over the entire duration of the study.

The naphthalene disk cassettes were appropriately curved to conform to surface curvatures of the upper arm, lower arm, thigh, and calf of the manikin. Casting cassettes used for the chest were not curved. The curved disks expose an elliptic rather than circular surface. The elliptic surface area of each cassette disk was measured, shown in Table 2, and properly quantified (during evaluation of the \dot{m} term in Equation (1)).

In Table 3, h_c was calculated using equation (5), without the $P_{AM,n}$ factor, and subsequently compared to data calculated using Nishi and Gagge's predictive equation [1970a].

With the correction factor $P_{AM,n}$, the convective transfer coefficient h_c was computed and the results presented in Table 4. The h_c shown represent regional values at the specific sites. For each study run, h_c was averaged over the 55 minute experiment period. The results in Table 4 are the average of 15 runs.

DISCUSSION

In order to facilitate the rate of naphthalene sublimation, the environmental chamber temperature needed to be maintained as high as tolerable. In this study, 30°C was chosen. At this temperature, most human subjects will, to a greater or lesser extend, perspire. Once perspiration occurs, it will invariably contaminate the naphthalene, and render any naphthalene weight measurement useless. To avoid the problem of perspiration contamination, a life-size, stationary copper manikin was used. Since we were interested only in the convective heat loss, a manikin also eliminated any confounding evaporative contribution usually involved with human subjects.

The logarithmic mean density factor of naphthalene sublimating in air $P_{AM,n}$ is a necessary correction factor which results from diffusion of air toward the naphthalene surface due to an air partial pressure gradient [ASHRAE Fundamentals, 1985; Fobelets and Gagge, 1988]. Conventionally, for the water vapor - air interface, P_{AM} is approximately equal to unity and thus often ignored. For the naphthalene - air interface, our results showed that this value is very different from unity. To determine $P_{AM,n}$, h_c was first computed using equation (5) sans the $P_{AM,n}$ factor, then compared to known h_c data of comparable air velocity environment. In Table 3, $h_c / P_{AM,n}$ in column [1] was computed using the naphthalene mass loss data from the rotating arm mass transfer experiment. For comparable data, a Nishi and Gagge [1970a] predictive equation was employed. From analysis of their extensive naphthalene- h_c study data, Nishi and Gagge obtained the following power function regression equation:

$$h_c = 8.60 \cdot u^{0.531} \quad (7)$$

where u denotes air velocity in m/s, and $0.2 < u < 2.0$ m/s. Equation (7) enables prediction of h_c from air velocity measurements. Column [2] in Table 3 resulted from operating Equation (7) on the rotating arm air velocity data. Comparison of the two columns of data yielded the $P_{AM,n}$ values in column [3], for the ten rotational speeds. $P_{AM,n}$ is apparently a function of air velocity. Following Nishi and Gagge's example using power function equation, Equation (8) was obtained from regression analysis ($r^2=0.94$).

$$P_{AM,n} = 0.326 \cdot u^{0.126} \quad (8)$$

$$0.18 \text{ m/s} < u < 1.8 \text{ m/s}$$

However, because air velocity does not appear as a variable in the heat-mass transfer analogy Equation (5), $P_{AM,n}$ as a function of air velocity cannot be substituted in directly. An average value $P_{AM,n}$ was used instead in Equation (5). From the results in Table 3, an average $P_{AM,n}$ of 0.319 ± 0.0295 was obtained. Obviously, the application of this average value is limited by $0.183 < u < 1.83$ m/s. Notice in Table 3, for the regional air velocities encountered on the manikin, 0.4 - 0.7 m/s (from Table 1), the average $P_{AM,n}$ value is very close to the actual computed $P_{AM,n}$. For example, at 0.548 m/s (9 rpm), the actual computed $P_{AM,n}$ was 0.311. Although not presented explicitly as logarithmic mean density factor $P_{AM,n}$, Nishi and Gagge [1970b] also gave an indication that a new heat mass transfer correction factor of 0.37 (1/2.7) was essential when operating at the naphthalene - air interface (see footnote of Table 1 in Nishi and Gagge [1970b]).

In Table 3, the range of $P_{AM,n}$ for the naphthalene - air interface is only approximately one third of the often neglected P_{AM} (≈ 1.0) of the water vapor - air interface. Therefore, unknowingly assuming a unity value $P_{AM,n}$ for the naphthalene - air environment will result in substantial overestimation of the derived convective heat transfer coefficient h_c . This type of overestimation was reported by Sparrow and Tien [1977], and evident in an initial report on h_c determination using an articulated manikin by Chang et al [1988].

Incorporating the mean density factor $P_{AM,n}$ (average value 0.319), regional h_c for the stationary manikin was computed and is presented in Table 4. The range of h_c was between 5 - 8 W/(m²·K). Since the naphthalene disks conformed to the body segment curvatures and sat directly over the specific body sites, local h_c over

individual body sites were measured, rather than some average h_c values for entire body segments.

CONCLUSION

Using the sublimating naphthalene disks technique, the regional convective heat transfer coefficients (h_c) on the human body were determined on a stationary, life-size manikin. Based on the Chilton-Colburn j-factor heat-mass analogy, the sublimating naphthalene disks becomes a straightforward technique for determining the convective heat transfer coefficient. This analogy as shown in this report eliminates the many very elaborate extrapolations employed by other techniques. The need to represent the human body as an assembly of cylindrical segments of various sizes is thereby unnecessary. The necessity of determining characteristic diameters for the representative cylindrical segments, whose dimensions are critical in Nishi and Gagge's formulation, is eliminated. The extensive analogies applied using the relationship between the various nondimensional quantities of heat transfer, e.g. Nusselt, Prandtl, Reynolds, Schmidt, Sherwood, and Stanton numbers, are also reduced.

In this report, the logarithmic mean density factor for naphthalene sublimating in air ($P_{AM,n}$) was also determined. $P_{AM,n}$ for the naphthalene -air interface is only approximately one third of the often neglected P_{AM} (≈ 1.0) of the water vapor - air interface. $P_{AM,n}$ is apparently a function of air velocity. An regression equation: $P_{AM,n} = 0.326 \cdot u^{0.126}$ was calculated ($r^2=0.94$) for $0.18 \text{ m/s} < u < 1.8 \text{ m/s}$. Because the Chilton-Colburn heat-mass transfer analogy equation does not operate on air velocity as a variable, an average value $P_{AM,n} = 0.319$ was

used in computing h_c . $P_{AM,n}$ is an essential property for extracting the correct h_c value from the naphthalene mass transfer measurement data. An overestimation of the convective heat transfer coefficient h_c results without suitable assessment of this factor.

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Figure 1

[S.KW. Chang and R.R. Gonzalez]

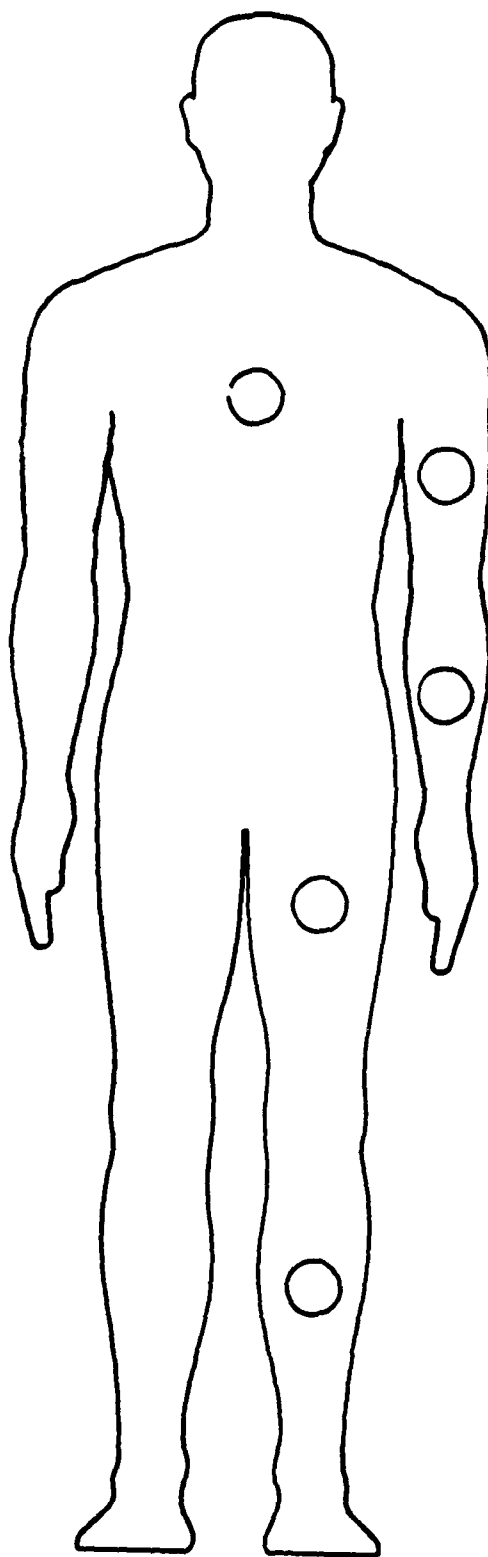


Table 1

[S.KW. Chang and R.R. Gonzalez]

naphthalene disk site	regional air velocity (m/s)	temperature (°C)
Upper Arm	0.61 ± 0.02	29.97 ± 0.11
Lower Arm	0.71 ± 0.01	29.91 ± 0.12
Thigh	0.42 ± 0.01	30.00 ± 0.13
Calf	0.69 ± 0.02	29.95 ± 0.11
Chest	0.49 ± 0.01	30.00 ± 0.13

Table 2

[S.KW. Chang and R.R. Gonzalez]

site	disk surface area (cm ²)
Upper Arm	19.23
Lower Arm	19.32
Thigh	18.85
Calf	19.32
Chest	18.09

Table 3

[S.KW. Chang and R.R. Gonzalez]

rpm	air velocity u (m/s)	[1]	[2]	[3]
		from Eqn. 5 $h_c / P_{AM,n}$	from Nishi & Gagge $h_c = 8.60 \cdot u^{0.531}$	ratio [2] / [1] $P_{AM,n}$
3	0.183	13.76	3.46	0.251
6	0.365	17.64	5.07	0.287
9	0.548	20.16	6.26	0.311
12	0.730	22.75	7.28	0.320
15	0.913	24.89	8.18	0.329
18	1.10	27.02	9.09	0.336
21	1.28	29.01	9.59	0.331
24	1.46	30.83	10.51	0.341
27	1.64	32.79	11.18	0.341
30	1.83	34.48	11.85	0.344

average 0.319 ± 0.0295

regression equation: $P_{AM,n} = 0.326 \cdot u^{0.126}$

Table 4

[S.KW. Chang and R.R. Gonzalez]

naphthalene disk site	local h_c $W/(m^2 \cdot K)$
Upper Arm	7.49 ± 0.133
Lower Arm	7.23 ± 0.122
Thigh	6.01 ± 0.110
Calf	7.78 ± 0.165
Chest	5.30 ± 0.120

Figure & Table Captions

Figure 1 Schematic diagram showing locations of the naphthalene disks on the manikin

Table 1 Regional air velocities and local temperature surrounding the stationary manikin

Table 2 Naphthalene disk surface areas

Table 3 Determination of $P_{AM,n}$ from the rotating arm mass transfer experiment
radius = 58.1 cm (from center of bar to center of mounted disk)
 h_c is in $W \cdot m^{-2} \cdot K^{-1}$

Table 4 Regional h_c on the stationary manikin